Satellite-Derived Tropical Cyclone Structure and Intensity

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LONG-TERM GOALS

To understand tropical cyclone (TC) structure (center fix, inner core characteristics, size, and intensity) and the time evolution from genesis to a mature storm while focusing on environmental conditions that impact rainband and inner core changes that are directly related to a storm's intensity and associated wind and rain fields.

OBJECTIVES

Develop accurate automated satellite-based techniques to estimate TC location, inner core characteristics, size, intensity and intensity changes under all conditions (e.g., 24 hr/day, any global location, and strengths ranging from tropical depression to Category 5). Create demonstration products that enable the TC community to more accurately assess a storm's location, track and intensity via the exploitation of multiple satellites via sensor data fusion.

APPROACH

Satellite sensors represent the only observing platform that can currently provide the geographic coverage, and spatial, spectral, and temporal sampling required to monitor TC parameters in a near real-time mode globally. This project will focus on developing new satellite-based tools that assist the TC community in mapping storm structure (location, inner core characteristics, size, and intensity). Long term efforts have focused on visible/infrared (vis/IR) imagery that provide 30-minute refresh within the tropical oceanic basins. This effort will exploit the data fusion possible by combining microwave imagers and sounders with the more traditional vis/IR sensors and take advantage of the inherent capabilities to view storm characteristics in all-weather conditions.

Combining digital data from a suite of geostationary (GEO) and low earth orbiting (LEO) satellites for near real-time applications on 4-7 ongoing storms is difficult in the research environment and can create chaos in an operational setting when multiple products need to be queried from different computer systems and visualization platforms. One of our goals is to simplify the GEO-LEO data fusion, while extracting the best traits from each digital data set and thus enhance the community's ability to accurately monitor global TCs.

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Previous efforts utilizing microwave imager data have outlined the ability to view storm structure generically, but have only recently delved into the more difficult quantitative analyses. Our project will enable the next step by recalibrating multiple sensors to a "standard" frequency that will permit advances in storm signals not feasible earlier. In addition, we plan to significantly add to the temporal sampling of TC intensity by incorporating new microwave sounders that will be in the operational constellations for years to come.

WORK COMPLETED

1. Created 1st ATMS TC intensity estimate algorithm using both simulated and real ATMS digital data sets and compared to multiple other satellite and in-situ data sets.
2. Nearing completion of ARCHER v3.0 which incorporates relative sensor-weighting based on the sources' respective confidence measures (collaboration with U. of Wisconsin-CIMSS).
3. Transitioned Special Sensor Microwave Imager Sounder (SSMIS) algorithm to extract storm intensity to corresponding 6.4 work unit (collaboration with U. of Wisconsin-CIMSS).
4. Collected multi-decadal digital data sets (~1TB) for the following passive microwave sensors (SSM/I: 1987-2011, SSMIS: 2003-2011, TMI: 1997-2012, AMSR-E: 2002-2011). Began collecting WindSat data from 2003-2012.
5. Recalibrated TMI 85 GHz brightness temperatures from to 89 GHz in order to mitigate large frequency dependent impacts encountered within tropical cyclone inner core convection (frozen hydrometeors) and thus enable consistent TC structure details using multi-sensor data sets (collaboration with Josh Cossuth, FSU PhD student).
6. Remapped TMI and AMSR-E microwave imager data using Backus-Gilbert resampling that permits the user to take full advantage of the nyquist sampling and extract the full information content for TC structural details (collaboration with Josh Cossuth, FSU PhD student).
7. Processed TMI and AMSR-E overpasses of all global TCs using "best track" data sets from both NHC and JTWC (collaboration with Josh Cossuth, FSU PhD student).

TECHNICAL RESULTS

Section 1: NPOESS Preparatory Program (NPP) Advanced Technology Microwave Sounder (ATMS) TC Intensity Estimates (CIMSS Collaboration)

Advanced Technology Microwave Sounder (ATMS) data has been used to develop and refine an algorithm similar to Advanced Microwave Sounder Unit (AMSU) designed to estimate TC intensity. MSLP estimates now employ a channel-weighted approach using ATMS channels 8 and 9. The MSLP anomaly contribution for these channels are estimated individually, and then the two estimates are weighted according to the respective channel's estimated contribution to the TC pressure anomaly in the same way that the AMSU and Special Sensor Microwave Imager Sounder (SSMIS) intensity algorithms are done. A separate MSLP estimate is then produced using the maximum T_B anomaly for channels 7, 8 and 9. In most cases the max anomaly will be located in channels 8 and 9 because hydrometeor scattering tends to depress the sensed T_B for channel 7. However, for storms where the eye is sufficiently large, channel 7 may yield a larger magnitude T_B anomaly. Using the maximum T_B

of each of the three channels allows information from channel 7 to impact the MSLP estimate in cases where the TC warm core anomaly may be located lower in the atmosphere than is typically observed well via microwave sounders. Figure 1 below shows the relationship between the predicted ATMS max T_B anomaly (predicted using AMSU T_B anomalies convolved to ATMS scan resolution) and aircraft-measured MSLP anomalies.

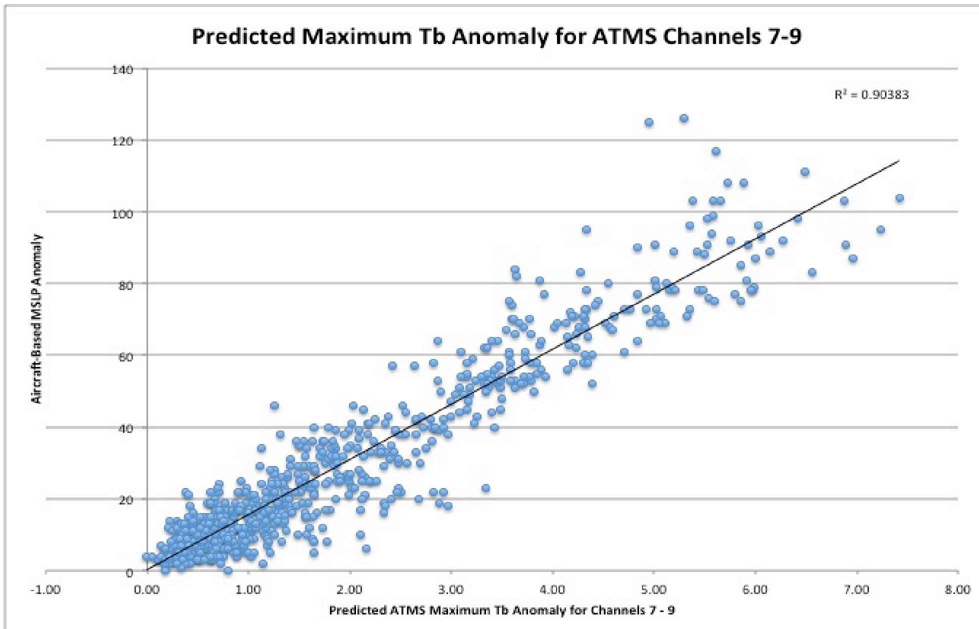

Figure 1: ATMS estimated maximum T_B anomaly derived from convolved AMSU for channels 7-9 compared to measured MSLP anomalies from in-situ reconnaissance aircraft.

ATMS MSLP intensity estimates can now be produced as soon as a new S-NPP pass becomes available. Additional work is needed to automate the process using orbital parameters to estimate satellite/TC intercept times. Relationships will also be developed to estimate the maximum sustained winds (Vmax).

ATMS is the sounder with the highest spatial resolution footprint currently in orbit (at nadir), however some TCs will have an eye size small enough to still result in some under-sampling of the TC warm core aloft. As resolution decreases away from nadir, this under-sampling increases and results in intensity estimates that have a weak bias. This can be modeled and corrected for as we have done previously for AMSU. Atlantic hurricane activity continues to be below normal in 2013 and is currently at only 30% of normal Accumulated Cyclone Energy (ACE). Consequently, there have been no CAT 3 or stronger hurricanes (TCs likely with eye structures) sampled by aircraft in the Atlantic since S-NPP was launched (Sandy was close, but was a hybrid system off the US coast). As a result there are as of yet no coincident aircraft observations available to study and verify the ATMS MSLP bias as a function of TC eye size. So in order to investigate the bias, select cases from 2012-2013 in all ocean basins were chosen based on high confidence of the operational best track intensity estimates using both objective and subjective methods. MSLP estimates were derived from ATMS T_B anomalies and then compared to the difference between the ATMS scan resolution, using the field of view located closest the TC center location and eye size. This relationship is shown in Fig. 2 below. While

the number of sample cases is small, the bias is as expected with a tendency to be too weak when the TC eye is small compared to the ATMS scan resolution.

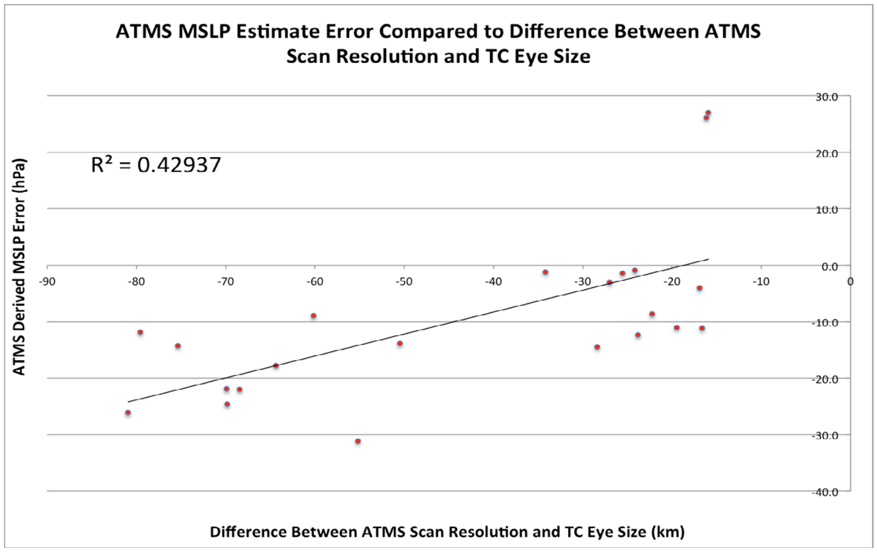

Figure 2: MSLP estimate bias from ATMS as a function of TC eye size. The average error for this N= 24 sample is - 9.4 hPa. The data sample includes Super Typhoon Usagi (17W) from 2013.

The strongest TC of the 2013 NH season thus far is Super Typhoon Usagi (17W), which reached a maximum estimated intensity of 140 knots. Usagi was a large typhoon that developed a small eye. Objective microwave-based eye size estimates from the UW-CIMSS ARCHER algorithm reached as small as 12 km in diameter (estimated surface eye size). The UW-CIMSS MIMIC imagery for Usagi at 12-hour intervals starting at 0600 UTC on September 19 is shown in Fig. 3, depicting Usagi's small eye and the eyewall replacement cycle (ERC) that Usagi underwent during this period. This storm permitted an evaluation of the ATMS intensity algorithm as S-NPP passes were available during much of Usagi's life. A plot of bias-corrected (using the relationship in Fig. 2) MSLP estimates compared to best estimates of true MSLP is shown in Fig. 4 below. Usagi passed over an island station in the Luzon Straits which observed a pressure of 922 hPa at 2300 UTC on Sept. 20 with winds of 80 kts. This results in an estimated MSLP of 915 hPa, in good agreement with the ATMS MSLP estimate.

As more ATMS data becomes available, additional adjustments to the algorithm will become possible. Currently the algorithm uses T_B anomalies derived using the along-track Tbs. Future work will involve developing limb-corrected T_Bs as well as a hydrometeor scattering correction to address under-sampling that results from the scattering attenuation within the core field of view (FOV) in the scan.

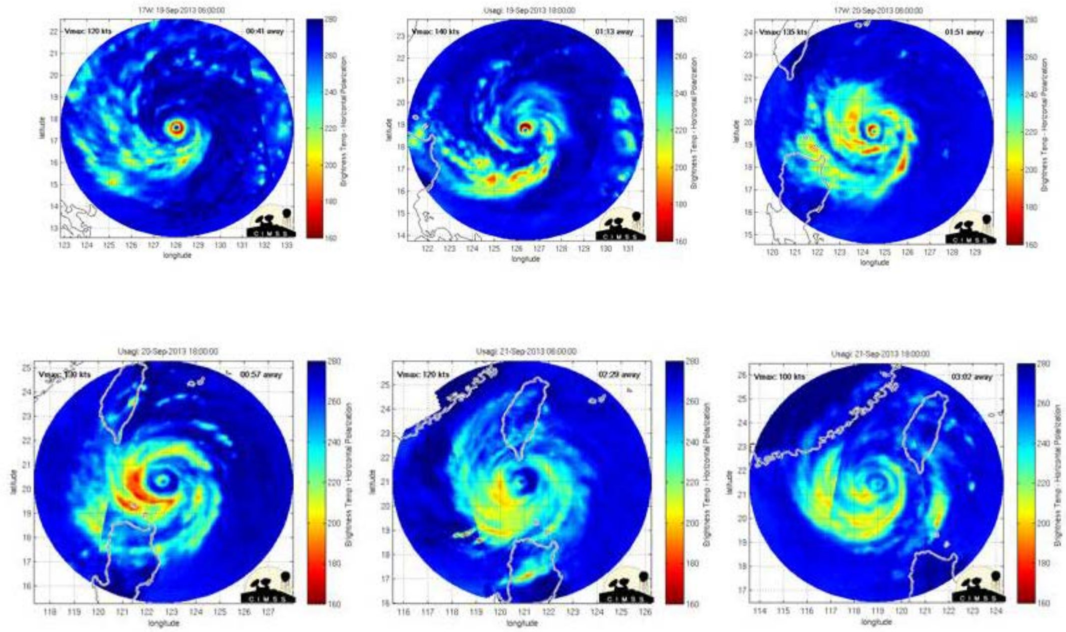

Figure 3: CIMSS MIMIC T_B images for Super Typhoon Usagi at 12-hour intervals starting Sept 19 0600 UTC.

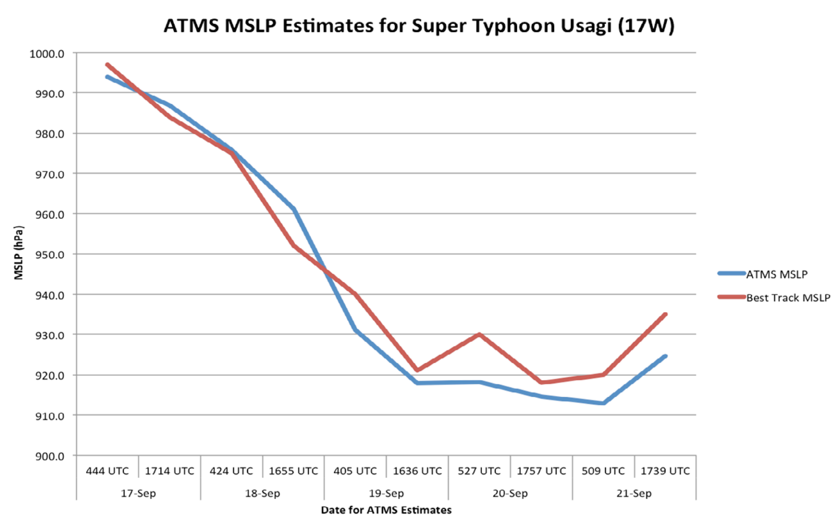

Figure 4: MSLP estimates derived from ATMS for Super Typhoon Usagi compared to "best track" estimates of MSLP.

Section 2: Automated Tropical Cyclone Center Location Identification (CIMSS Collaboration)

The prior year's report presented ARCHER v2.0, which performs objective TC center-fixing on single images (microwave, IR or visible), and notional ARCHER v3.0 ("ARCHER-Track"), which employs ARCHER v2.0 track fixes into a single evolving TC track using the highest-confidence sources plus recent track history. We are finalizing the calibration of these algorithms for a Dec. 2013 release. The

development process includes four new case studies from the West Pacific basin, demonstrating the importance of relative source-weighting based on the sources' respective confidence measures (Fig. 5). These case studies confirm the parameterizations for ARCHER v2.0 and v3.0 developed initially using North Atlantic basin TCs. As with the North Atlantic cases, ARCHER-Track uses the high temporal resolution center fixes from GEO-IR imagery during more intense stages of the TC for more precise storm-tracking, and relies on more accurate but less frequent LEO microwave image fixes during weaker stages (both on the way up and down in intensity). The relative confidence of an image's center-fix is described by the output parameter "alpha," which constrains the probability density function of center-fix error. Alpha is inversely proportional to the spread of the probability density function (a Poisson distribution).

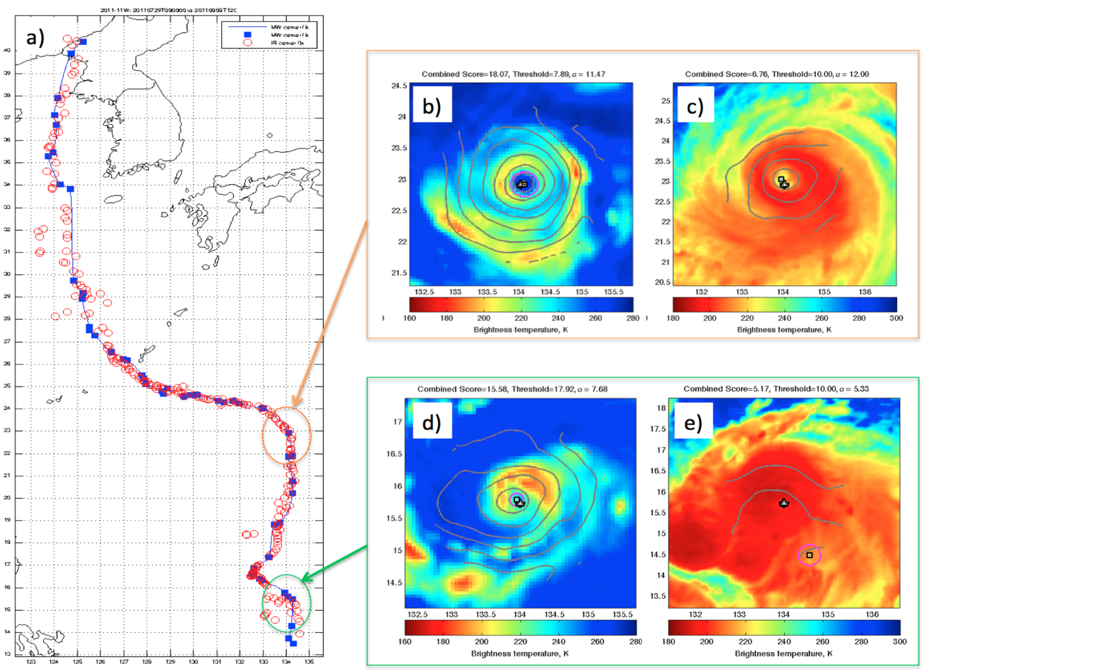

Figure 5. Example of ARCHER results for Super Typhoon Muifa, 2011 (11W). a) ARCHER track positions for history-guided microwave center fixes (blue) and individual MTSAT-2 IR center fixes (red), b) center-fix scoring analysis for a SSMI/S microwave brightness temperature (T_B) image during the storm's intensification and c) center-fix scoring analysis for an MTSAT-2 IR image (same time), showing that high temporal resolution and track updating can be achieved at this stage, d) accurate center-fix scoring analysis during early formation stage with microwave, and e) low-confidence scoring analysis using IR imagery show that in these TC stages the objective tracking relies mainly on passive microwave imagery.

We have also begun collaborating with numerical weather prediction (NWP) model developers on how to use ARCHER structure/organization scores on HWRF output in the form of synthetic microwave imagery. The results will provide a potential validation tool for the model's short-term forecast storm evolution (i.e. changes in eyewall structure, size and continuity) and improve ARCHER intensity estimates by tracking modeled microwave retrieval patterns in high temporal resolution. We have so far completed the demonstration phase to show that synthetic microwave imagery is entirely workable in the ARCHER intensity retrieval scheme (Fig. 6).

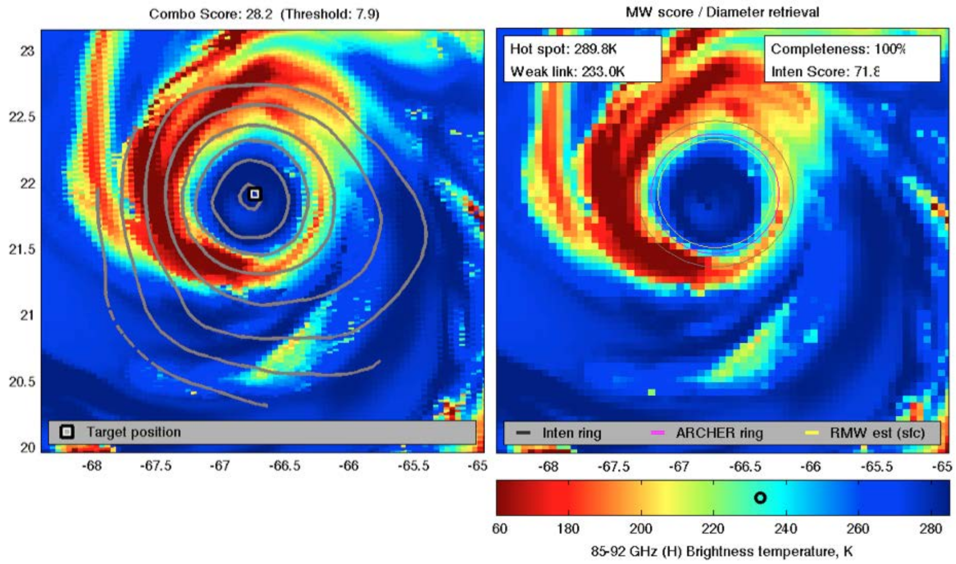

Figure 6. ARCHER center-fixing for Hurricane Earl (2010) on 1 Sept 0000 UTC (110 kt max wind), using an 85 GHz (H) synthetic retrieval from the HWRF model fields. a) Score fields (contours), target position (square). b) ARCHER eyewall diameter retrievals: ring of minimum T_B (gray), inner ring of the convective eyewall activity (magenta), and estimated radius of maximum winds (yellow). Text boxes in the upper corners indicate statistics of the 85 GHz T_B field consistent with a TC having maximum winds > 85 kts.

Section 3: Tropical Cyclone Structural Evolution

TC structural evolution from genesis to peak intensity and subsequently during decay is difficult to monitor, but vital to better comprehend how TC's form, morph into storms reaching Category 5 and then decay. We simply do not fully understand the various pathways during a TC's lifespan since we have not had a consistent all-weather 24/7 observing tool.

Satellite GEO vis/IR data have rapid temporal updates and geographically cover the TC tropical oceanic basins well, but cannot view key storm structure due to upper-level cloud obscuration that frequently hides vital mid and low-level TC features (rainbands and eyewall development) as noted in Figure 7. While microwave imagery provides key details on rainband organization, eyewall formation, and other important inner core structural changes due to its ability to see through non-raining clouds (Hawkins et. al., 2001 and Hawkins and Velden, 2011), coincident Dvorak enhanced IR imagery is severely limited by the central dense overcast (CDO) and detects a complete eyewall 24 hours after microwave imagery. Thus, real-time warning intensities based solely on Dvorak analyses would significantly lag the true TC intensity and the bogus vortex for both the regional and global Navy models would be adversely impacted.

In addition, the frequency of problems with upper-level clouds occurs ~ 36% of the time in the western pacific (WPAC), when using the Advanced Dvorak Technique (ADT) derived scene types. Figure 8 highlights the variability from year to year using ADT applied to MTSAT digital data is relatively small, although storm to storm variations can range from near zero to 100% (not shown).

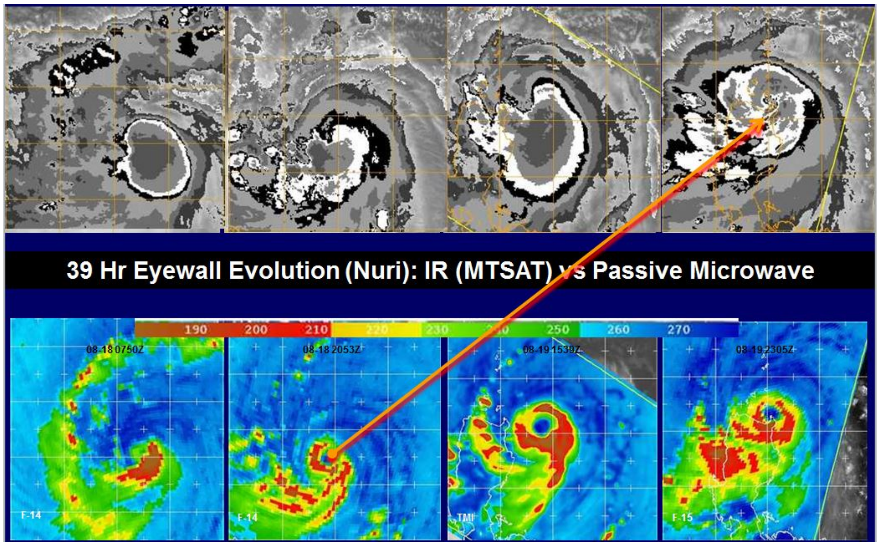

Figure 7. Coincident GEO IR (Dvorak enhancement, top panel) and passive microwave imagery from multiple sensors highlighting the ability to view typhoon Bopha inner core structure via the ice scattering channel T_B (85-91 GHz).

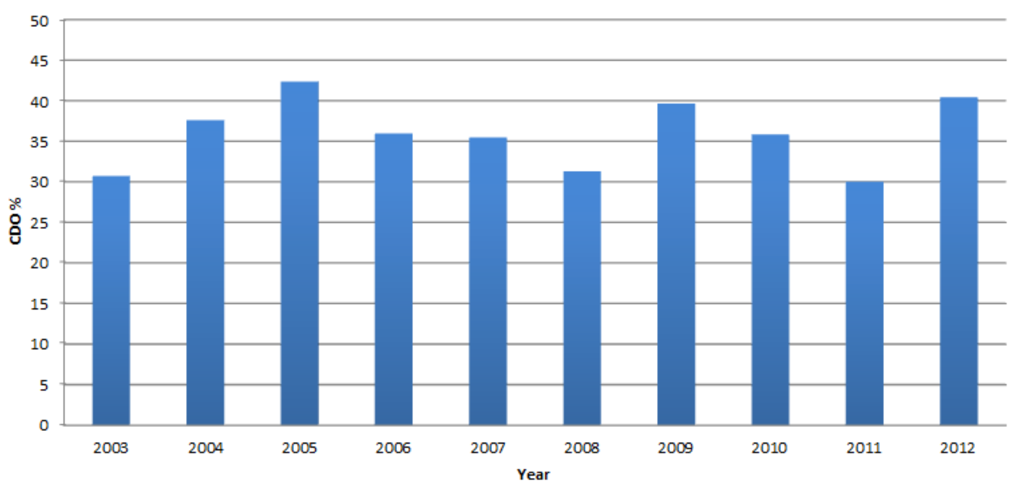

Figure 8. Upper-level cloud obscuration occurrences (%) for WPAC storms using GMS-6/MTSAT digital data processed by ADT to calculate scene types (CDO, embedded center, and irregular CDO) with upper cloud issues (courtesy CIMSS).

The geographic location of upper-level clouds causing problems with accurate center fixes and Dvorak intensity estimates is highly scattered as might be expected, since storm evolution (initial intensification from depression to typhoon with central dense overcast, CDO conditions, interaction with troughs aloft, shear) varies dramatically from storm to storm. Since TC genesis and tracks cover much of the WPAC basin in any given year, cloud obscuration can occur throughout the domain (Fig. 9) and frequently happens during critical stages of Navy/DOD decision making associated with fleet and aircraft sorties as TCs recurve and threaten Guam, the Philippines, Okinawa, and Japan.

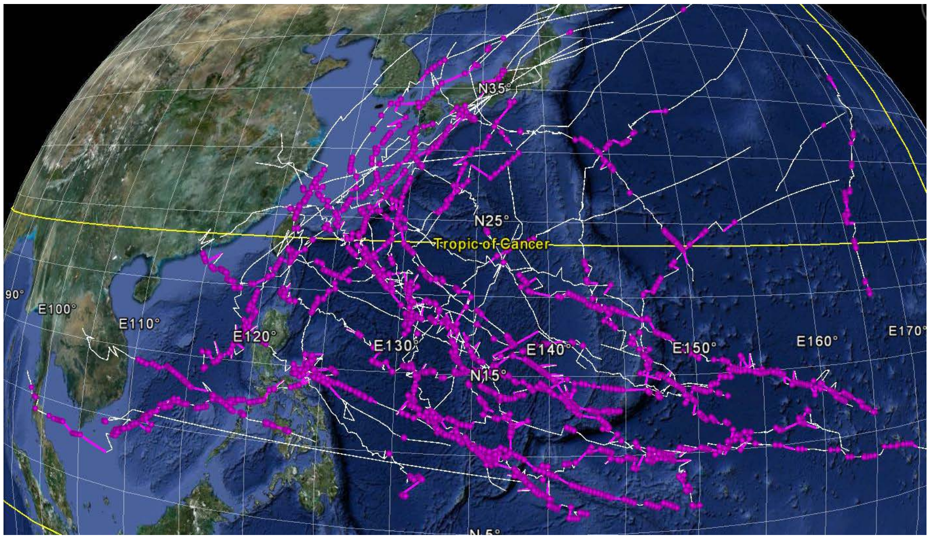

Figure 9. Purple dots denote locations of WPAC TCs that have upper-level cloud issues that preclude accurate center fix extraction via GEO IR data and present problems for Dvorak intensity estimates (courtesy JTWC).

To mitigate the temporal sampling dilemma associated with LEO sensors, our team has created an unprecedented TC microwave imager data base by accessing high quality global passive microwave imagery digital data sets for the sensors listed in Fig. 10. The specific time frames and sources listed in Table 1. The data set represents a total size of ~ 600 GB and has been matched up with best tracks provided by both the National Hurricane Center (NHC) and JTWC. Thus, coincident microwave imagery from the ~ 100 TCs/year globally has been extracted, providing unique temporal sampling via the use of both research and operational sensors.

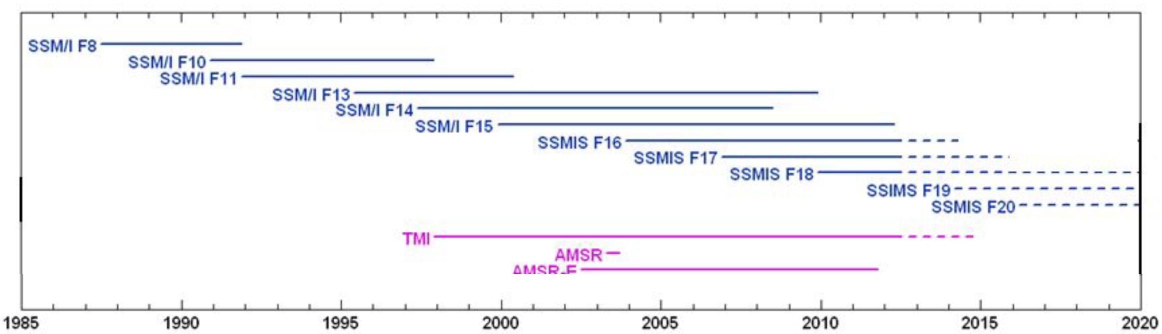

Figure 10. Timeline for the duration of each passive microwave imager potentially available for the study of TC inner core structure characteristics.

Table 1: Listing of digital passive microwave imagery available for TC overpass study.

Sensor	Timeframe	Source
SSM/I:	1987-2011	Colorado State University
SSMIS:	2003-2011	Colorado State University
TMI:	1997-2012	NASA JPL
AMSRE:	2002-2011	NASA JPL
WindSat:	2003-2011	NRL DC

Once we have intercalibrated 85, 89, and 91 GHz and remapped the data via the Backus Gilbert technique (Poe, 1990) as outlined in last year's report and soon to be published (Yang, et al, 2013), we then need to create a methodology to analyze and extract critical details from the very large TC microwave digital data base. Fig. 11 is a Hurricane Katrina example where 100 km range rings have been overlain. Azimuthal interrogation of the data set can then proceed and potentially provide temporal information highlighting rainband evolution during intensity and inner core changes.

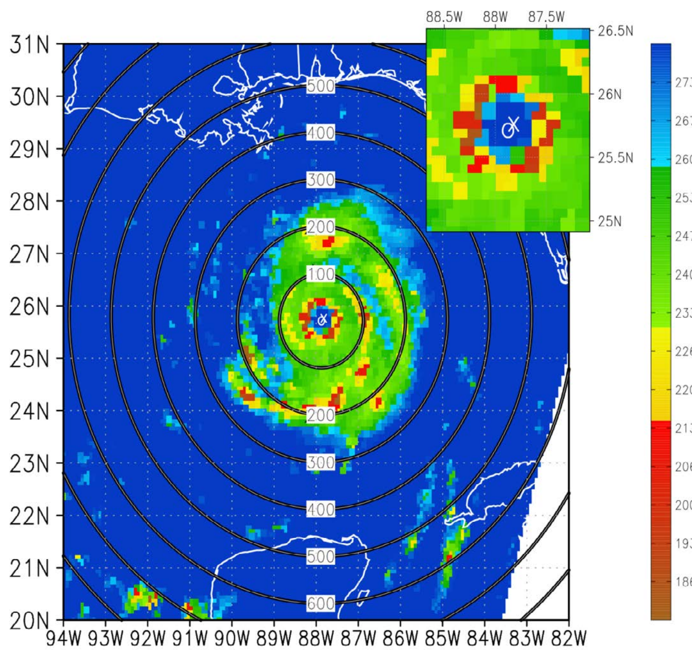

Figure 11: Hurricane Katrina ice scattering channel T_B (color wedge on the side) highlighting the spiral rainbands and inner core with range rings (100 km intervals) overlain (courtesy of Josh Cossuth).

One of the tasks is how to extract those TC structural features that are key to storm genesis, intensification, and eventual decay. Fig. 12 depicts an azimuthal relative view that permits the analyst another perspective that is much easier to interpret in determining the orientation of spiral rainbands and inner core structure. When the high temporal digital data for a given storm is examined using the combined resources of a consistent SSM/I, SSMIS, TMI, AMSR-E, and WindSat data set, then we have the best chance since the 1st launch of SSM/I in 1987 of understanding TC structural time evolution. This data set then can assist in answering fundamental questions pertaining to the reasons

for storm intensity changes, eyewall replacement cycles, and whether these are dynamical in-storm processes and/or impacted by their environment (we have collected coincident data sets on shear, SSTs, and potential interactions with troughs aloft).

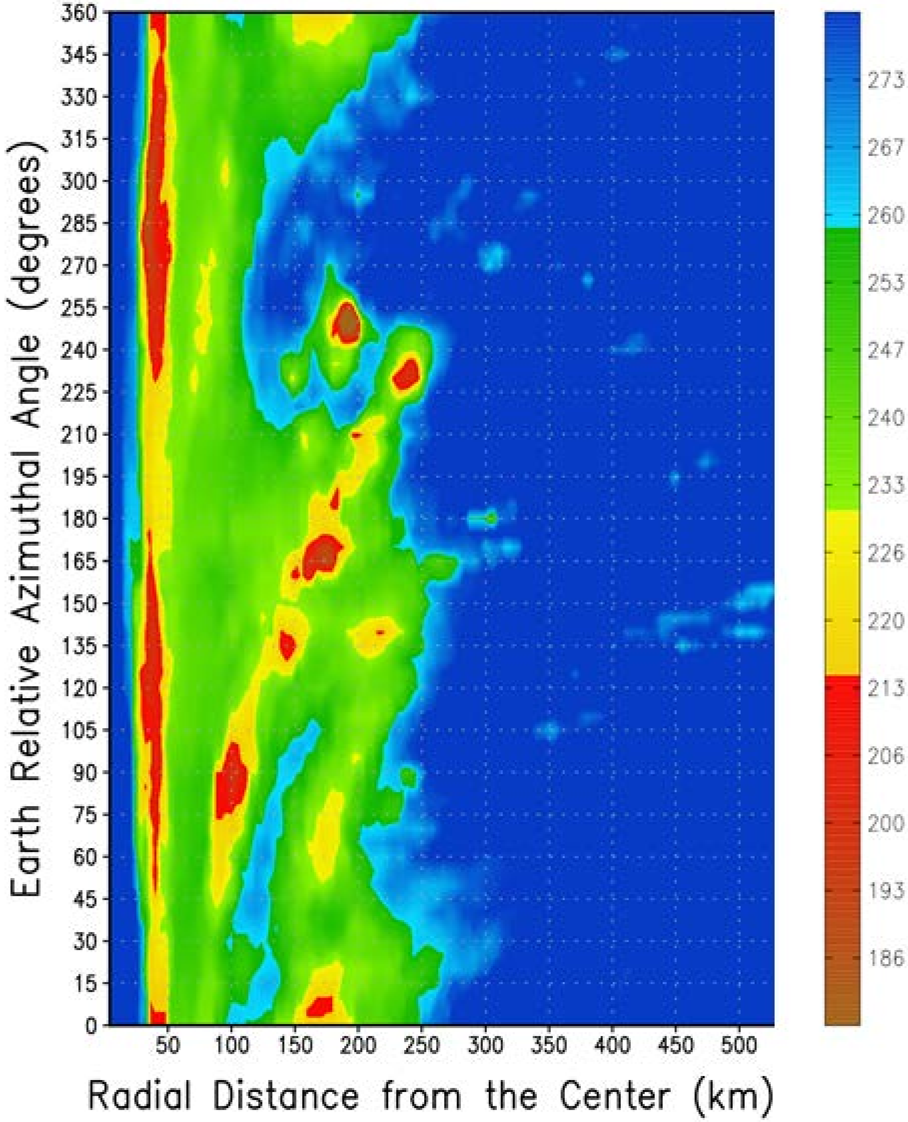

Figure 12: Earth relative azimuthal view of Hurricane Katrina T_B enabling a better perspective for mapping TC spiral rainbands and inner core structure using Fig. 11 digital data (courtesy of Josh Cossuth).

This 1st of its kind digital data set will then be used to study TC structural evolution from birth, to maximum intensity, and through decay. The data set will permit discoveries not earlier possible on the potential multiple "pathways" TCs possess; a) eyewall formation, b) secondary eyewall formation, cycles, and inner eyewall decay, c) new insight into rainband and inner core impacts due to shear, cool sea surface temperatures and dry air intrusions (such as Saharan Air Layer or mid-latitude sources). Coincident digital data sets depicting shear, SSTs and ocean surface wind vectors (QuikSCAT, ASCAT scatterometer, and WindSat) will be available for analysis.

IMPACT/APPLICATIONS

The frequent, high quality, remapped and frequency corrected digital data set covering microwave imager overpasses from 1987 to the present will provide the team and the community with the first ever digital data set needed to study storm inner core evolution. While microwave imager data has proven useful for near real-time warning applications, the full potential of gleaning storm evolution has not been realized due in part to the lack of a consistent high resolution data set covering multiple decades and oceanic basins.

TRANSITIONS

The SSMIS derived TC intensity estimate algorithm has been transitioned to a corresponding 6.4 work unit funded by PEO C4I PMW-120, where an ongoing near real-time demo is underway with validation in concert with JTWC. The automated microwave center finding method (ARCHER) is now a mature algorithm, and has been recently funded as a new FY-14 project by the NOAA Joint Hurricane Testbed program at NHC. ARCHER holds promise in greatly aiding the Tropical Analysis and Forecast Branch (TAFB) efforts to keep up with storm center fix gyrations when using 15-minute interval GOES digital imagery. Currently, manual satellite derived fixes are only done at 3 hourly intervals and thus do not take advantage of the temporal sampling routinely provided.

RELATED PROJECTS

This project is closely related to a 6.4 effort sponsored by the Program Executive Office for C4I&Space/PMW-120 entitled "Tropical cyclone intensity and structure via multi-sensor combinations", funded under PE 0603207N. The 6.4 project serves as the transition vehicle, works closely with JTWC, the National Hurricane Center and the Central Pacific Hurricane Center and serves as the conduit to new products at FNMOC. Feedback from JTWC, NHC, CPHC and the TC research community has been extremely positive at multiple technical conferences and via email sent directly to NRL-MRY.

This project works closely with JTWC, NHC, CPHC and FNMOC to understand the needs of the operational TC community via routine emails, phone calls and technical conferences (AMS, IHC, TCC, and IWTC). Feedback is routinely solicited from all operational partners in order to understand how the 6.2 efforts outlined here can best be aligned to answer real world requirements and needs.

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